



POLARIZATION OF LYMAN- $\alpha$  RADIATION FROM ATOMIC  $^1\text{H}$  HYDROGEN  
EXCITED BY ELECTRON IMPACT FROM NEAR-THRESHOLD  $\sim 101800\text{eV}$

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## ABSTRACT

The polarization of Lyman- $\alpha$  radiation, produced by electron impact excitation of atomic hydrogen, has been measured for the first time over the extended energy range from near - threshold to 1 800 eV. Measurements were obtained in a crossed-beams experiment using a silica-reflection linear polarization analyzer in tandem with a vacuum ultraviolet (VUV) monochromator to isolate the emitted line radiation. Comparison with various theoretical calculations shows the present experimental results are in good agreement with theory over the entire range of electron impact energies and, in particular, are in excellent agreement with the latest theoretical convergent close coupling (CCC) calculations of Bubelev et al. (1995). The present polarization data are significantly different from the previous experimental measurement of Ott et al. (1970).

## 1.0 INTRODUCTION

Polarization of atomic line radiation has been of general interest since its early discovery in the Zeeman effect, and there is now a relatively large body of data available on polarization of electron impact-induced radiation (McConkey et al. (1988)). Polarization measurements in the vacuum ultraviolet (VUV) present particular difficulties for experimentalists. Since most of the standard birefringent materials do not transmit in the VUV, reflection devices with low reflection coefficients must be used. The problem is further compounded by the instability of some of the commonly used optical materials (such as LiF), the lack of reliable high quality optical data for some materials and, in some cases, low polarizance. In addition, reflection devices are susceptible to changes in their reflection characteristics from the accumulation of surface films, even in systems employing clean vacuum (Jammond et al. (1989)).

Much of the available experimental VUV polarization data have been obtained by the Windsor group and refer to the excitation of the rare gases and various molecules (see, for example, Westerveld et al (1985), Malcolm et al (1979), Ihuschilt et al (1981), Dassen and McConkey (1981)).

Accurate experimental values for the polarization of radiation produced by electron impact excitation provide a sensitive test for theory by determining the relative populations of the degenerate magnetic sublevels in the excitation process. In addition, since electron impact excitation cross sections are typically measured in a crossed-beams configuration, with the emitted radiation detected at  $90^\circ$  to the electron beam axis, polarization measurements are required to correct these data in order to obtain values for the integral cross section.

The first measurement of the polarization of Lyman- $\alpha$  radiation produced by electron impact excitation of atomic hydrogen was reported by Fite and Brackmann (1958). Values for the polarization were determined from the angular distribution of the Lyman- $\alpha$  radiation. However, the data were essentially of a preliminary nature and have very large error bars.

The only subsequent measurement reported in the literature is that of Ott et al. (1970). These authors used a tungsten oven to dissociate molecular hydrogen and an oxygen filter and iodine vapor photon counter to isolate and detect the Lyman- $\alpha$  radiation reflected from a LiF crystal mounted at the Brewster angle in their polarization analyzer. The polarization data of Ott et al (1970) have been widely used in the literature to correct the H(2P) cross section data of Long et al. (1968) for polarization effects in order to obtain values for the integral cross section.

Accurate polarization data play a pivotal role in the measurement of integral cross sections, not only for comparison with various theoretical approximations but, as importantly, for establishing the secondary standards for spectroscopic modeling of

stellar and planetary atmospheres. In this paper, new measurements are presented of the polarization of Lyman- $\alpha$  radiation produced by electron impact excitation of atomic hydrogen in the extended energy range from near-threshold to 1800 eV. The present experimental approach takes advantage of recent developments in VUV polarization analyzers (Chwirot et al. (1993)) and H-atom sources (Slevin and Stirling (1981)) which are capable of producing atomic densities 3 orders of magnitude greater than previously available. Furthermore, the use of a 0.2-meter VUV monochromator in the present experimental apparatus permits the unambiguous isolation of the Lyman- $\alpha$  radiation. This leads to a more accurate determination of the molecular contribution to the signal than in previous work and opens the possibility of extending the present measurements in the future to higher members of the Lyman series.

## 2.0 POLARIZATION OF LINE RADIATION

Dipole radiation emitted in the relaxation of an atom excited by electron impact will, in general, be polarized due to the anisotropy of the collision process. The present experiment has a crossed-beam geometry, with the incident electron beam defining an axis of symmetry. It can be shown (see, for example, Andersen et al. (1988)) that for such cylindrical symmetry the radiation can be completely characterized by a single integrated Stokes parameter  $S_1$ , which is defined by

$$S_1 = \left[ \frac{I(0^\circ) - I(90^\circ)}{I(0^\circ) + I(90^\circ)} \right] \quad (1)$$

where  $I(0^\circ)$  (also referred to as  $I_{\parallel}$ ) and  $I(90^\circ)$  (or  $I_{\perp}$ ) are the photon intensities observed at  $90^\circ$  to the electron beam axis with electric vector parallel or perpendicular to the beam, respectively. This parameter is often given the symbol  $P$  ( $= S_1$ ), and is referred to as the polarization of the radiation.

A comprehensive theoretical treatment of the polarization of radiation was first given by Percival and Seaton (1958). More recently, Blum (1981) and Andersen et al. (1988) set polarization measurements in the wider context of a description of collisionally excited atoms in terms of state multipoles. Excited atomic states populated by electron impact on ground state atoms evolve under the influence of spin-orbit and hyperfine interactions and decay with the emission of radiation. The relationship between the cross sections for populating the various degenerate magnetic sublevels of the excited state and the resulting polarization is characterized by a set of constants which depend on the relative magnitudes of these interactions. For the Lyman series the polarization takes the following form

$$P(\text{IIP}) = \frac{100(Q_0 - Q_1)}{(2.375 Q_0 - 3.749 Q_1)} \quad (2)$$

where  $Q_M$  is the cross section for excitation of the magnetic sublevel  $M$  related to the orbital angular momentum and it is assumed that hyperfine interactions and radiation damping can be neglected.

At high energies, where the Bethe-Born approximation is expected to be valid, the polarization  $P$  of electron impact induced radiation from an atomic state  $j$  can be calculated from a Born expression derived by McFarlane (1974). This high energy limit of the polarization has been discussed in some detail by Heddle (1979), who shows that the parameter  $P$  can be represented in this approximation by the expression

$$P = P_0 \left[ 3 - \ln \left( 4c_j \frac{E}{R} \right) \right] \left[ \left( 2 - P_0 \right) \ln \left( 4c_j \frac{E}{R} \right) + P_0 \right]^{-1} \quad (3)$$

where  $P_0$  is the polarization at threshold produced by electron impact of monoenergetic electrons of energy  $E_j$ ,  $c_j$  is a parameter which describes the angular distribution of the scattered electrons, and  $R$  is the Rydberg constant. The parameter  $P_0$  can be calculated exactly from angular momentum conservation considerations and has a value of 0.42 for  $nP$  excitations (Percival and Seaton (1958)). Using a Born approach to the excitation, Inokuti (1971) has obtained a value of 0.408 for  $c_j$ . With these values for the constants  $P_0$  and  $c_j$ , equation (3) determines the high energy Born limit for the polarization.

One consequence of the above formulation is that the polarization has a value of zero at an energy given by  $E = c^3 R / 4c_j$ . Using the above value for  $c_j$ , the polarization is zero at an impact energy of 167 eV. An experimental determination of this quantity is therefore of considerable interest.

Finally, experimental observations of emitted radiation made at an angle of  $90^\circ$  to the electron beam axis must be corrected for the polarization of the radiation in order to determine the integral cross section for the excitation process. Such raw experimental data yield values of the apparent cross section ( $Q_{90}$ ) which are related to the true integral cross section ( $Q_\infty$ ) by

$$Q_T = Q_{90} \left( 1 - \frac{P}{3} \right) \quad (4)$$

Measurements of the polarization are thus not only of interest in determining magnetic sublevel cross sections, but also to provide a means for correcting polarization sensitive data.

### 3.0 EXPERIMENTAL APPARATUS

#### 3.1 Experimental Apparatus

The experimental apparatus consists of an electron impact collision chamber equipped with an atomic hydrogen source, in tandem with a 0.2 meter VUV monochromator (resolving power 250) and silica reflection linear polarization analyzer (Chwirot et al. (1993)) positioned after the exit slit of the monochromator. The electrostatic electron gun and monochromator systems have been described in detail in an "earlier publication (James et al. (1997)).

*COMMENTS*  
*Electro gun*  
The use of an electrostatic electron gun over the entire energy range from near-threshold to 1800 eV is an important feature of the present experimental configuration. As pointed out by Ott et al. (1970), polarization measurements using magnetically confined electron beams may be subject to systematic errors due to spiraling and other effects associated with magnetic field confinement. This is especially true at low energies close to threshold, and results in a reduction in the observed polarization. While electrostatically focused electron beams present the experimenter with the difficult task of minimizing energy-dependent beam overlap variations, a crucial problem for a measurement of the optical excitation function, beam overlap effects are not important in polarization measurements since the experimental data relate to a *ratio* of  $I_{\parallel}$  and  $I_{\perp}$  signals measured at each energy and overlap variations cancel.

A Faraday cup designed to eliminate backscattered secondary electrons is used to monitor the electron beam current (typically 5  $\mu$ A). The energy spread of the electron beam is approximately 0.3 eV, with an uncertainty in the beam energy of  $\pm 0.1$  eV, as measured from the appearance potential for excitation of the Lyman- $\alpha$  transition.

The atomic hydrogen source has been described in detail by Slevin and Stirling (1981). Hydrogen molecules are dissociated in a discharge, excited within a radio frequency (RF) cavity, resonant at 36 MHz. Hydrogen atoms effuse from a water cooled pyrex discharge tube, past a quartz photon trap and through a 1 mm capillary into a field-free interaction region where they are moss-fired by the electron beam. Photons emitted from the interaction region are dispersed by the VUV monochromator, with slit widths chosen to ensure adequate separation of atomic line emissions. The VUV monochromator provides precise wavelength selection, a factor which is critical in quantifying the molecular contribution to the observed Lyman- $\alpha$  signal. The use of an oxygen filter in the previous work of Ott et al. (1970) introduced an uncertainty as to precisely what spectrum was transmitted to the detector.

The polarization analyzer is shown in Figure 1 and has been described in detail by Chwirot et al. (1993) who also compare its performance to other analyzer designs. The optical constants of the silica mirror require an angle of incidence of  $40^{\circ}$  to reflect a single plane of polarization only. A value of 0.85 ( $\pm 0.03$ ) for the polarizance  $\epsilon$  (or extinction ratio for the two orthogonal polarizations) of the analyzer used in the present

measurements was measured by Chwirot et al. (1993) for Lyman- $\alpha$  radiation using the geometry shown in Figure 2. A channeltron positioned at the reflector angle is used as the photon detector with a CM-coated entrance cone to enhance the quantum efficiency at Lyman- $\alpha$ . The use of a fully characterized (and stable) silica reflection polarization analyzer in the present experiment represents a considerable advantage over previous measurements which employed a LiF reflector. LiF crystals are hygroscopic and degrade over a period of time when exposed to the atmosphere. It is thus difficult to maintain their long term stability and their use as polarizers adds a measure of uncertainty to the experimental data.

in order to eliminate any polarization effects that may be induced by the monochromator and detector systems, the grating is rotated such that the plane defined by the monochromator entrance slit and optic axis is at  $45^\circ$  to the electron beam axis (James et al. (1997)). The theoretical basis for this orientation is described in detail by Clout and Iddles (1969) and Donaldson et al (1972).

Polarization measurements are made in the conventional manner by aligning the analyzer axis such that signals proportional to  $I_{//}$  and  $I_{\perp}$  reach the detector. These correspond to values of  $45^\circ$  and  $135^\circ$ , respectively, for the angle  $\beta$  shown in Figure 1. This is achieved by rotating the analyzer mirror and detector assembly using a stepper motor. Using an identical polarizer to that in the present experiment, Chwirot et al. (1993) reported measurements of the full angular distribution of Lyman- $\alpha$  radiation, fitted to the well known functional form, confirming the validity and accuracy of this experimental procedure.

The entire experimental system is interfaced to a PC which controls the electron beam energy and the stepper motor used to change the polarization analyzer orientation. Measured signals are normalized to the electron beam current and hydrogen source pressure, eliminating these potential sources of systematic error. Data are accumulated in a multiple scanning mode to reduce the effects of any drifting in other experimental parameters.

### 3.2 Correction procedure for molecular contribution

Since the hydrogen beam is not fully dissociated, the observed photon signal at  $121.57\text{\AA}$  contains a contribution from molecular emission which must be quantified. The molecular component results from Lyman- $\alpha$  radiation produced by dissociative excitation of  $\text{H}_2$ , as well as radiation from molecular bands transmitted by the bandpass of the monochromator ( $1.7\text{ nm}$  at typical slit widths of  $600\text{ }\mu\text{m}$ ). In order to correct the measured polarization data for this molecular contribution, the dissociation fraction must be measured, together with the polarization of a pure molecular hydrogen target produced with the RF discharge off.

The dissociation fraction is established in the manner described by James et al. (1997) by tuning the monochromator to an  $I_2$  molecular band at 1100i (with the bandpass adjusted to exclude any atomic component from Lyman- $\alpha$ ) and measuring the molecular emission with the discharge on and off at the same hydrogen source driving pressure and electron beam current. The dissociation fraction  $D$  is then related to these two signals  $S_1(\text{on})$  and  $S_2(\text{off})$  by the relationship

$$1 - D = \left( \frac{T_2}{T_1} \right)^2 \frac{S_1}{S_2} \quad (5)$$

where  $T_1$  and  $T_2$  are the effective kinetic temperatures in the gas beam with the discharge on and off, respectively. Woolsey et al. (1986) and Forand et al. (1988) measured these kinetic temperatures in a similar source and found that the two temperatures were equal, confirming the reasonable assumption that the source produces a thermal beam of hydrogen. A typical value for the measured dissociation fraction is  $(0.65 \pm 0.02)$ .

If the signals measured at the two orthogonal orientations of the polarization analyzer axis are defined as  $I^+$  and  $I^-$  (corresponding to  $I(135^\circ)$  and  $I(450^\circ)$ , respectively), and the subscripts 1 or 2 correspond to signals produced by atomic or molecular hydrogen targets, respectively, then for the pure molecular beam produced with the RF discharge off, the measured molecular polarization ( $P_{(112)}$ ) is given by

$$P_{(112)} = \frac{I_2^+ - I_2^-}{I_2^+ + I_2^-} \quad (6)$$

With the RF discharge on the beam contains both hydrogen atoms and molecules, and the ratio of atoms to the total number of particles in the beam is given by the dissociation fraction  $D$ . Under these conditions

$$\begin{aligned} I^+ &= I_1^+ + (1 - D)I_2^+ \\ \text{and} \quad I^- &= I_1^- + (1 - D)I_2^- \end{aligned} \quad (7)$$

Thus the apparent polarization ( $P$ ) measured with the RF discharge on is given by

$$P = \frac{I^+ - I^-}{I^+ + I^-} = \frac{I_1^+ - I_1^- + (1 - D)(I_2^+ - I_2^-)}{I_1^+ + I_1^- + (1 - D)(I_2^+ + I_2^-)} \quad (8)$$

$$\begin{aligned} \text{Defining} \quad I_1^+ + I_1^- &= I_1^0 \\ \text{and} \quad I_2^+ + I_2^- &= I_2^0 \end{aligned} \quad (9)$$



then 
$$P = \frac{I_1^+ + I_1^- + (1-D)(I_2^+ - I_2^-)}{I_1^0 (1-D)1}; \quad (10)$$

and

$$P + P(1-D) \frac{I_2^0}{I_1^0} = \frac{I_1^+ - I_1^-}{I_1^0} + \frac{(1-D)(I_2^+ - I_2^-)}{I_1^0} \quad (11)$$

The polarization of the radiation resulting from excitation of hydrogen atoms alone,  $1'(1\ 1)$  is then given by

$$1'(1\ 1): \frac{I_1^+ - I_1^-}{I_1^0} \quad (12)$$

Finally we obtain

$$I' + P(1-D)\kappa = I'_{H1} + (1-D)\kappa P_{(H2)} \quad (13)$$

$$\text{where } \kappa = \frac{I_2^0}{I_1^0}$$

$$\text{and } P_H = I' + (1-D)\kappa(P - P_{(H2)}) \quad (14)$$

If we define  $I^0 = I_1^+ + I_1^-$

$$= I_1^0 + (1-D)I_2^0 \quad (15)$$

then 
$$\kappa = \left[ \frac{I^0}{I_1^0 - (1-D)} \right]^{-1} \quad (16)$$

Thus the polarization for atomic hydrogen ( $1'1$ ) can be obtained from separate measurements of the polarization with the RF discharge on and off (giving  $P$  and  $P_{(H2)}$ , respectively), together with a measurement of the dissociation fraction  $D$ . The parameters  $I^0$  and  $I_2^0$  also needed to evaluate  $\kappa$  are obtained by summing the signals detected at the two orthogonal polarization analyzer orientations with the discharge on and off, respectively.

The above analysis assumes that the polarizance of the analyzer is unity. The true polarization of the atomic radiation is obtained by dividing the result derived using equation (14) by the polarizance  $\epsilon$ . The present data are corrected by the polarizance value of 0.85 for Lyman- $\alpha$  measured by Chwiot et al. (1993).

### 3.4 Resonance trapping

Since trapping of the resonance Lyman- $\alpha$  radiation by ambient atomic hydrogen generally leads to a reduction in the polarization, it is essential to ensure that the column density of atomic hydrogen is such that the probability of absorption of a Lyman- $\alpha$  photon en route to the detector is negligibly small. To ensure the absence of resonance trapping effects in the present experiment, measurements are made under conditions where the detected photon signal is proportional to the hydrogen source pressure. Operating under Knudsen conditions at the beam source preserves a linear relationship between the source pressure and the number density in the interaction region. Previous measurements with this source described by James et al. (1997) verify the absence of resonance trapping and associated depolarization effects for source pressures less than  $4.6 \times 10^{-11}$  Torr. The present experiment was carried out at a source pressure of  $\sim 40$  mTorr.

## 4.0 RESULTS AND DISCUSSION

The experimental data for the Lyman- $\alpha$  polarization are tabulated in Table 1 and cover the range of electron impact energies from near-threshold to 1800 eV. Table 1 also includes, for comparison, the previous experimental data of Ott et al. (1970) and the CCC calculations of Bubelev et al. (1995). These data are illustrated graphically in Figures 3 and 4, as well as the predictions of McFarlane (1974). The errors on the experimental data correspond to one standard deviation in the statistics, with an additional contribution from identifiable sources of systematic error as outlined in the Error Analysis Appendix.

Clearly the experimental data are in excellent agreement with the CCC results over the entire range of energy, except for a single CCC datum at 14 eV. Since the CCC results may be subject to some numerical instabilities at energies close to threshold due to strong resonance effects in the cross section at these energies (Bray (1997)), this particular disagreement can not be considered significant. Overall, the agreement between the CCC theory and experiment can be considered as excellent. Since data for experimental measurements of the 2P excitation (James et al. (1997) from this laboratory) and the same CCC theory are also in excellent accord, these polarization measurements further confirm the essential validity of the CCC approximation over the entire range of energy from threshold up to the Born region at 1800 eV.

The experimental data are also in good agreement with the Born-McFarlane curve at energies above 100 eV. This is a lower energy for Born validity than that obtained for the cross section measurements of James et al. (1997), where the Born region was reached only at energies  $> 1000$  eV. From an experimental point of view this convergence of experiment and theory at high energies provides strong evidence that our experimental method is relatively free from any unknown systematic effects (for instance, in the polarization of the analyzer, or the presence of low energy secondary electrons). In this respect it is noteworthy that the Ott et al. (1970) data at high energies (limited to 700 eV)

lies significantly above the theoretical results, suggesting the presence of some small systematic effect in these data,

The present polarization data for Lyman- $\alpha$  arc  $\sim 10\%$  than the earlier data of Ott et al (1970) over most of the range of energies reported (by approximately  $\sim 10\%$  in the energy region from threshold up to  $\sim 100$  eV) suggesting some systematic difference between the two experiments. The use of a monochromator for wavelength selection, permitting accurate subtraction of the molecular component of the Lyman- $\alpha$  signal, as well as a more stable polarization analyzer, would suggest fewer sources of systematic error in the present experiment.

, the discrepancy between our data and those of Ott et al cannot be explained in terms of an inaccurate determination of the polarizance of either analyzer. Ott et al (1970) measured a value of 0.94 for the polarizance of their LiF Brewster angle analyzer by a technique in which an identical crystal was used to polarize an unpolarized beam of photons produced by electron impact excitation of atomic hydrogen at high energy. The electron energy used by Ott et al (1970) for this measurement is not specified but is presumably around 200 eV since the radiation produced at any other energies will be polarized. The apparent polarization measured by Ott et al under these conditions was assumed to be given by  $P = \epsilon^2$ . Subsequent measurements on a similar design of LiF reflection polarizer by Lippler et al (1985) yielded a similar value for  $\epsilon$  of 0.9. However, if the Ott polarization data are corrected using a polarizance of 0.9 the values for their data will increase by approximately 4%, resulting in an even larger discrepancy. As far as the value of 0.85 ( $\pm 0.03$ ) used for the polarizance in the present experiment is concerned it also seems unlikely that this could be in significant error given the recent measurement of Chwirot and Slevin (1992). Indeed, the present data are in excellent agreement with all theories at 54.4 eV and any change in the value of the polarizance  $\epsilon$  would scale all of our data, including that at 54.4 eV. Finally, the excellent agreement with Bethe-Born at high energies confirms the accuracy of the polarizance of our analyzer. In these circumstances, we argue that the present data provide the best determination of the polarization of Lyman- $\alpha$  radiation in the energy range from near-threshold to  $\sim 2$  keV.

The experimental data are also compared with other theoretical calculations in Figure 5. The theoretical results correspond to the R-matrix and Close Coupling Approximations (CC) (Callaway et al (1994) and Wyngaarden and Walters (1986)); a Distorted Wave Born Approximation calculation (DWBA) (Madison et al (1994)); and finally the Eikonal Born Series Expansion (EBS) (Joachain et al (1989)). Our polarization data are in excellent agreement with CC and DWBA theoretical calculations in the energy range from 50 to 100 eV and the agreement is particularly good at the important energy of 54.4 eV. At energies from threshold to 40 eV, however, our data are consistently below the predictions of all the theoretical calculations, whereas in the higher energy region above 100 eV our data lie above these predictions. Both of the CC calculations show strong resonance features in the threshold energy region. Because the energy resolution of our

electron beam is -0.5 eV this resonance behavior would not be seen in our data. Notwithstanding this, the CC results in this energy region averaged over our energy resolution are still significantly higher than our data. The agreement between theory and experiment in the energy range from 100 eV to 300 eV is only fair and the theoretical data lie outside the error bars of the experimental data for all of the points shown.

The experimental determination of the energy at which the polarization is zero gives a value of  $Y$  for the parameter  $P_0 = R/4c_j$  and a value of  $Z$  for the Bethe Parameter  $c_j$ . This compares with the widely used value of 0.408 based on the calculations of Inokuti(1971).

It is also noteworthy that the experimental polarization data for Lyman- $\alpha$  do not tend to the Percival and Seaton (1958) limit of 0.4?, at threshold, an effect which has also been seen in the polarization results for the resonance lines of helium (see McConkey? ??). However, it should be noted that the threshold polarization may well be masked by the electron beam energy resolution of ~0.4 eV obtaining in the present experiment.

## 5.0 ERROR ANALYSIS

A comprehensive analysis of statistical and systematic errors was performed in order to determine the limiting accuracy of the present measurements. The total error in the measurement relates to the errors in the individual terms in equation (14), namely:

- (1) the statistical errors in the observed count rates  $I_i^+$  and  $I_i^0$
- (2) the error in the dissociation fraction  $D$ ,
- (3) the error in the polarizance  $c$  (since the value of  $I_{H'}^+$  in equation (14) must be divided by  $c$  in order to obtain the true polarization).

The error in the observed polarization is calculated in the usual way by carrying out a Taylor Series expansion of the quantity  $\left[ \frac{P_H}{c} \right] [P_H/c]$  with respect to all of the above quantities and then combining the individual error contributions in quadrature. Typical values for the individual relative errors at an energy of 54.4 eV are 2.7% (discharge on count rates), 0.2% (discharge off count rates), <0.10% for  $D$  and 3.5% for  $c$  combined in quadrature to yield a total error of  $\pm 0.6$  in a measured polarization of 10.5%.

As expected, the largest errors occur at electron impact energies where the cross section results in lower signal rates. For example, at energies near threshold the total error in the measured  $II(2P)$  polarization is 1%, whereas in the region of the peak cross section for excitation of Lyman- $\alpha$  (around 40-70 eV) the total error reduces to approximately 0.5%.

The silica reflector in the polarization analyzer will, in practice, accept a cone of angles of incidence of the detected radiation on the mirror surface about the nominal angle of incidence of  $70^\circ$ . The VUV monochromator has an  $f/4.5$  optical system with the diffraction grating used which would result in an acceptance cone half-angle at the reflector surface of  $6.3^\circ$ . However, aperture stops are included both at the exit of the interaction region and at the entrance of the analyzer that effectively restrict the acceptance cone half-angle of the analyzer to approximately  $3^\circ$ . The resulting depolarization effect can be shown to be negligible (Chwirot and Slevin (1993)).

It might be argued that our polarization data could be affected by  $1(2s)$  metastables being quenched within the interaction volume by any stray electric fields, possibly produced by space charge in the electron beam. Such a process would cause a reduction in the measured polarization.

Finally, it should be noted that the observed photon signal will include a contribution from  $nP$  states populated by cascade processes from higher-lying states rather than by direct excitation. Heddle and Gallagher (1989) have used the horn cross section calculation of Vainshtein (1965) to estimate this cascade contribution in the case of Lyman- $\alpha$  to be of the order of 2% from states with  $n=3-6$ . If it is assumed that cascade processes populate the magnetic sublevels equally, then the measured polarization values at energies above the energetic threshold for cascading transitions should be reduced by this factor. However, due to the considerable uncertainties involved in this correction procedure and since the changes involved are very small it was decided not to attempt to make a cascade correction. In these circumstances our data should be viewed as representing an upper limit at least in so far as cascade effects are concerned.

## 6.0 CONCLUSIONS

The polarization of Lyman- $\alpha$  radiation produced by electron impact excitation of atomic hydrogen in the energy range from threshold to 1800 eV has been measured in a crossed-beam experiment using a silica reflection linear polarization analyzer. The present experimental results have been compared to the data of Ott et al (1970) (in the case of Lyman- $\alpha$ ) and to the latest theoretical calculations. They are in excellent agreement with the CCC results of Bray and his collaborators over the entire range of energy. They are also in good agreement with R Matrix and close-coupling calculations in the low energy regime. The present data are significantly different from the previous experimental data of Ott et al (1970), and it is argued that the present data are likely to be more accurate.

## ACKNOWLEDGMENTS



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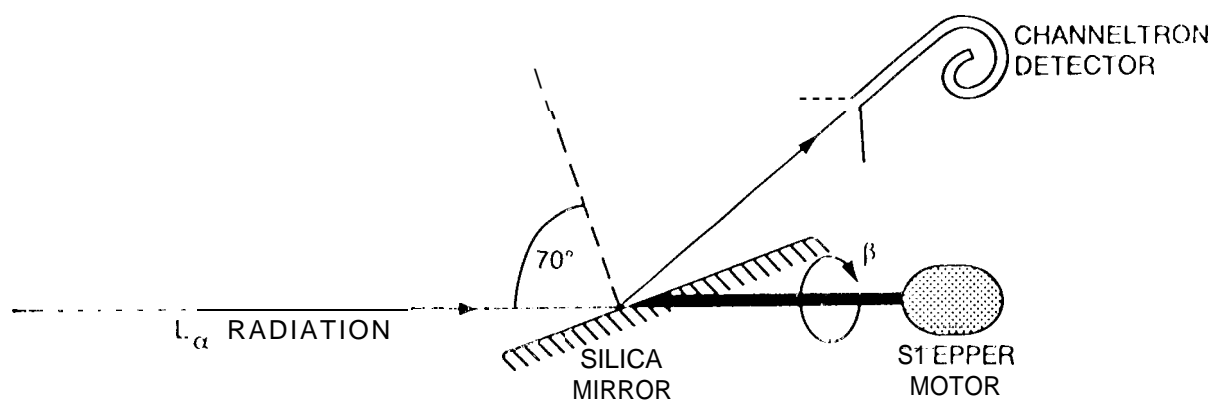
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	Energy (eV)	Present work	Error in present work	Ott et al. (1970)	Error in Ott et al.	Born (McFarlane (1974))	Kingston and Walters (1990)	Burke et al. (1993)	vanWyngaarden and Walters (1995)	Callaway et al. (1994)	COC (Bray 1996)
1	10.15			0.130	0.005						
2	10.20			0.159	0.007						
3	10.30			0.140	0.007						
4	10.40			0.158	0.006						
5	10.50	0.1289	0.0120	0.139	0.006						
6	10.60			0.142	0.005						
7	10.70			0.137	0.005						
8	10.80			0.141	0.004						
9	10.90			0.165	0.005						
10	11.00	0.1371	0.00930	0.171	0.005						
11	11.10			0.175	0.005						
12	11.20			0.190	0.005						
13	11.30			0.186	0.005						
14	11.40			0.193	0.005						
15	11.50	0.1778	0.00930	0.209	0.006						
16	11.60			0.221	0.006						
17	11.70			0.222	0.007						
18	11.80			0.228	0.005						
19	11.90			0.241	0.007						
20	12.00	0.2361	0.0104	0.225	0.007					0.2520	
21	12.10			0.242	0.006					0.2616	
22	12.13									0.2650	
23	12.17									0.2674	
24	12.20			0.223	0.007					0.2698	
25	12.24									0.2721	
26	12.30			0.229	0.005						
27	12.31									0.2754	
28	12.38									0.2771	
29	12.40			0.240	0.008						
30	12.44									0.2742	
31	12.49									0.2548	
32	12.50	0.2401	0.0133	0.245	0.006					0.2592	
33	12.51									0.2633	
34	12.53									0.2683	
35	12.54									0.2662	
36	12.55									5.2327	
37	12.57									0.2987	
38	12.58									0.3007	
39	12.59									0.2993	
40	12.60			0.241	0.007						
41	12.61									0.2899	
42	12.62									0.2659	
43	12.63									0.2818	
44	12.65									3.2765	
45	12.66									0.2694	
46	12.70			0.234	0.008						
47	12.80			0.221	0.005						
48	13.00	0.2542	0.0105	0.245	0.005						
49	13.10			0.250	0.008						
50	13.20			0.226	0.007						
51	13.30			0.236	0.008						
52	13.40			0.220	0.006						
53	13.50			0.245	0.008						
54	13.60			0.219	0.008						
55	13.70			0.243	0.006						



	Energy (eV)	Present work	Error in present work	Ott et al. ('970)	Error in Ott et al.	Born (McFarlane ('974))	Kingston and Walters ('980)	Burke et al. ('953)	van Wymgaarden and Walters ('996)	Callaway et al. ('994)	CCC (Bray '996)
55	13.80			0.249	0.006						
57	14.00	0.2680	0.0108	0.243	0.006						0.3252
58	14.20			0.246	0.007						
59	14.30			0.229	0.007						
60	15.00	0.2697	0.0108	0.247	0.010						
61	15.00	0.2669	0.0106	0.236	0.010						
52	16.46									0.2860	
53	16.51										0.2740*
64	17.00	0.2714	0.0107	0.234	0.010						
65	18.00	0.2662	0.0105	0.253	0.010						
56	19.00	0.2617	0.0104								
57	19.58									0.2700	
58	20.00	0.2540	0.0101	0.231	0.009						
69	22.00	0.2537	0.0101								0.25222
70	25.00	0.2740	0.00950	0.216	0.008						
71	29.00										0.2075**
72	30.00	0.2085	0.00850	0.209	0.005						
73	35.00	0.1844	0.00790	0.171	0.007	0.244702					0.17232
74	35.40									0.1760	
75	40.00	0.1590	0.00710	0.156	0.004	0.20753*					
75	45.00	0.1445	0.00670			0.178966					
77	50.00	0.1304	0.00640	0.137	0.004	0.156185					
78	54.40	0.1182	0.00610			0.129564	0.0855	0.110	0.1060	0.10897	
79	60.00	0.1071	0.00590	0.109	0.004	0.121928					
80	70.00	0.08230	0.00550	0.0900	0.005	0.0958530					
81	80.00			0.0740	0.005	0.0776992					
82	85.00	0.05290	0.00510			0.0696513					
83	90.00			0.0550	0.006	0.0624016					
84	100.0	0.04940	0.00520	0.0520	0.004	0.0498277	0.0500	0.0390	0.03800	0.039060	
85	110.0			0.0530	0.005	0.0392553					
86	120.0	0.02540	0.00520	0.0510	0.005	0.0302035					
87	140.0			0.0400	0.005	0.0154202					
88	150.0	0.01390	0.00540			0.0092715*					0.0031600
89	150.0			0.0280	0.005	0.00375829					
90	180.0			0.0270	0.005	-0.00575379					
91	200.0	0.005500	0.00579	0.0200	0.007	-0.0137113	-0.0130	-0.0150		-0.020950	
92	250.0	-0.03650	0.00620	-0.00120	0.009	-0.0290544					
93	290.0					-0.0382558					-0.041910
94	300.0	-0.04540	0.04330	-0.0300	0.02	-0.040270*	-0.0400	-0.0423			
95	350.0							-0.0540			
96	400.0	-0.05430	0.00730	-0.0280	0.02	-0.0559563	-0.0580				
97	500.0	-0.05450	0.00780	-0.0480	0.02	-0.0556977	-0.0700				
98	600.0	-0.03820	0.00829	-0.0400	0.02	-0.0746910					
99	580.0						-0.0940				
100	700.0	-0.09790	0.00890	-0.0620	0.02	-0.0809648					
"c"	800.0	-0.07750	0.00940			-5.0850757					
102	700.0	-0.09370	0.01000			-0.0703548					
103	1000	-0.06960	0.0102			-0.0940335					
104	1200	-0.1147	0.0113			-0.0999971					
105	1400	-0.09170	0.0117			-0.104740					
106	1600	-0.1163	0.0125			-0.108635					
107	1800	-0.09320	0.0128			-0.111917					

# SILICA REFLECTION LINEAR POLARIZATION ANALYZER



## GEOMETRY OF THE POLARIZANCE MEASUREMENT

